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Optical high dynamic range acquisition of crack density evolution in cyclic loaded GFRP cross-ply laminates affected by stitching

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ABSTRACT

The fatigue crack density evolution in a cross-ply laminate where edge finish and stitching are taken into account is investigated. Diamond saw and water jet cutting are used to produce the test specimens and some of the specimens are polished afterwards. The crack density evolution and crack initiations are tracked automatically. It is shown that the number of cracks initiating at the edges for non-polished specimens are similar, whereas the diamond saw cut and polished specimens have fewer cracks at the edges, and the water jet cut and polished specimens have even fewer. In addition it is shown that the crack density is higher in the stitching areas than in the rest for polished specimens. This indicates that the stitching is highly governing of where cracks initiate and propagate in the specimens with limited edge defects. The same applies to real composite structures, which are negligibly affected by edge defects.

1. Introduction

Wind turbine blades (WTBs) are becoming bigger every year and often when the blade size is increased a new type certification is required. This certification can be obtained by complying with the design practice published by a certification body, e.g. DNVGL.

According to the DNVGL-ST-0376 standard [1], it is required that WTBs are designed against off-axis matrix cracks or Inter Fibre Failure (IFF) cracks using e.g. Pucks criterion [2]. These IFF cracks may be a design driver and hereby require reinforcement of the blade to comply with the standard. The Puck criterion relies on the transverse strength of the unidirectional (UD) layers used in the blade, which are obtained through testing of pure UD layers [3]. However, a WTB consists of laminates with layers in many directions, therefore, the constraining effect of the adjacent layers increases the apparent transverse strength of the UD layers as described in [4,5]. It is also shown in [6] for the fatigue case that the number of cycles to crack initiation is increased due to the constraining effect of layers in the load direction.

With higher transverse strength design values, less reinforcement is required, meaning a lower weight of the blade. Therefore, it is of great interest to obtain UD transverse strengths when the UD layers are embedded in a laminate. However, when testing laminates, the edge effect and defects induced by the cutting of the specimens may pollute the results and reduce the apparent strength. An indication that the edges affect the results is that most cracks during testing initiate from the edges [7–11]. The defects from cutting are usually considered alleviated by polishing the edges of the specimens [12–16]. However, very few studies have focused on the effect of the cutting technique prior to the polishing, and especially regarding fatigue. In [17,18] it is shown for static tensile tests that the strain at first crack onset is increased when diamond saw cut specimens are polished.

Today, more advanced cutting techniques such as water jet cutting is used when preparing specimens [19,11,20]. Specimens for static or fatigue testing cut with water jet are generally not polished afterwards. To the knowledge of the authors, it has not been investigated previously if the polishing after water jet cutting affects the static or fatigue properties.

Water jet cut specimens without subsequent polishing exhibit a very large scatter of two orders of magnitude in fatigue results regarding the number of cycles for off-axis crack initiation in multi directional laminates [11]. This means that when pure UD layers are tested, only the absolute weakest points are found and used to characterise the material. This is a conservative estimate of the actual properties of the material, thus leading to a conservative design. To design for anything other than the first off-axis crack requires information on the statistical distribution of the material properties. With a new technique developed by Glud et al. in [21], it is possible to obtain this statistical distribution with few test specimens. The Automatic Crack Counting (ACC) algorithm presented in [21] can detect all visible initiating cracks in a measuring area and track the propagation of these. Furthermore, this data can be used to accurately measure the crack density evolution in the measuring area and correlate this to a loss of stiffness for the

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specific lay-up. The crack density is obtained automatically meaning that the results are reproducible and not prone to human error as these measurements usually are. This makes crack density a much more viable metric for quantifying the damage state of composites.

Models have been developed where the crack density is used to predict the damage state of an arbitrary lay-up e.g. in Refs. [22–29]. When these models are further matured, it is possible to accurately predict the stiffness degradation of an arbitrary lay-up based on the crack density in the laminate. This allows for an accurate estimation of the structural integrity after IFF cracks have occurred in e.g. a WTB. It is the opinion of the authors of this work that these types of models with further maturing can be used to certify new WTBs with minor modifications to the guidelines in the DNVGL-ST-0376 standard. The modifications are already underway, because in the DNVGL-ST-0376 it is possible to obtain the type certification if it can be shown that IFF cracks sustained during testing do not affect the structural integrity of the WTB.

If crack density is to be used in a certifying context then it is necessary to understand which parameters influence the evolution of the crack density. The fibre mats used to manufacture WTBs are usually non-crimp-fabrics (NCF) where bundles of fibres in layers are stitched together and bundles of backing fibres in layers are used as well to ensure that the primary fibres keep their orientation. Backing layers are thin bundles of fibres on the backside of a fabric oriented at $\approx 90°$ to the rolling direction. Backing layers are particularly used when the fabrics are draped on steep curved surfaces [30]. It has been shown that the backing layers of the NCF fabrics have a large influence on when and where damage initiates and final failure occurs during fatigue testing of quasi UD laminates where only the backing layers are not parallel to the load direction [30–32]. In [30,31] there are also indications that off-axis matrix cracks initiate in the vicinity of stitching meaning that the stitching thread may act as an initiator of these cracks. The off-axis matrix cracks can in turn lead to local concentrations of fibre breaks especially in GFRP. Cross-ply laminates without backing layers were tested in [33] with the focus of relating the void content to a reduction in tensile and compressive strength. Most off-axis matrix cracks initiated from voids and a few initiated in areas with stitching. Typically in the cited works [30–33], the fibre breakages are localized in the vicinity of off-axis matrix cracks no matter if the cracks initiated from voids, backing layers, stitching, or off-axis layers. This indicates that any fibrous material not parallel to the load direction can act as initiators of Inter Fibre Failure (IFF), which causes localization of fibre breakage of load bearing fibres leading to final failure.

From this it is apparent that the backing and to some extent the stitching affects crack initiations, however, the crack density has not been considered in any of the cited works. Furthermore, the effect of the cutting technique on the crack density evolution through a fatigue test has not been considered. This leads to the following research questions, which are dealt with in this paper.

- Is the effect of the edge defects on the fatigue damage evolution different for specimens cut with water jet and diamond saw, respectively?
- Does polishing affect the fatigue damage evolution differently for specimens cut with water jet and diamond saw, respectively?
- Are the damages that occur in laminated composite structures e.g. wind turbine blades affected by the stitching in the NCF?

2. Specimen manufacturing and test setup

The specimen constituents and manufacturing process are described, followed by a description of the test setup and the post-processing routine based on the ACC algorithm with emphasis on the newly developed parts.

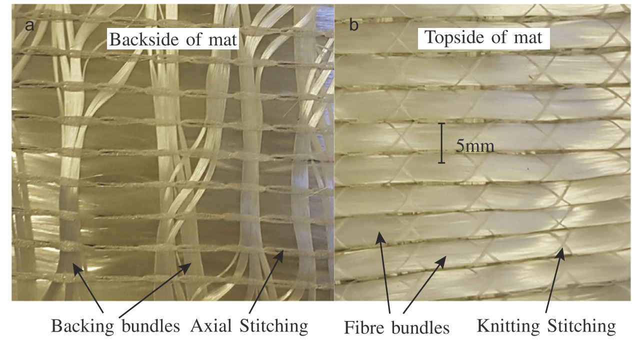

Fig. 1. Images of the dry fibre mats with stitching pattern used to manufacture the specimens. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1. Specimen manufacturing

The laminate used in this work is manufactured from Uniaxial 661 g/m^2 H-glass fibres with a matrix consisting of GT 105 Polyester through a Vacuum Assisted Resin Transfer Moulding process. The dry fibre mats are shown in Fig. 1 and in (a) the backing fibre bundles are shown, which are in a $\pm 80°$ pattern with approximately 8 wt%. The backing bundles are attached to the fibre bundles with a polyester stitching thread in a pattern as shown in Fig. 1(a and b).

The lay-up used in this work is $[0,90]_S$ where the backing layers are turned toward the outside of the laminate meaning that the 90 degree layer effectively has double thickness compared to the individual constraining layers, as shown in Fig. 2. The individual layers are 0.55 mm thick, and the total thickness is 2.2 mm. During infusion, the laminate is placed on a glass table to get a smooth surface to be able to detect the changes in light transmitted through the specimen during testing. End tabs made from GFRP are attached to the laminate after the infusion, and the specimens are cut using two different cutting techniques, where the final dimensions are shown in Fig. 3. 6 specimens are cut with a Diamond Saw (DS) and 6 are cut with Water Jet (WJ). Four of each of these specimen types are polished afterwards yielding two groups more, namely, Diamond Saw polished (DSp) and Water Jet polished (WJp). The polishing is done manually on a 'Struers Tegramin-30' with increasingly finer grain size down to 1 μm.

2.2. Test setup

The fatigue tests are performed in an Instron ElectroPuls E1000 with load control in Tension-Tension with an R-ratio of 0.1 with maximum load at 90% of the static transverse strength of the pure quasi UD with backing. Two light sources are used to illuminate the front and to

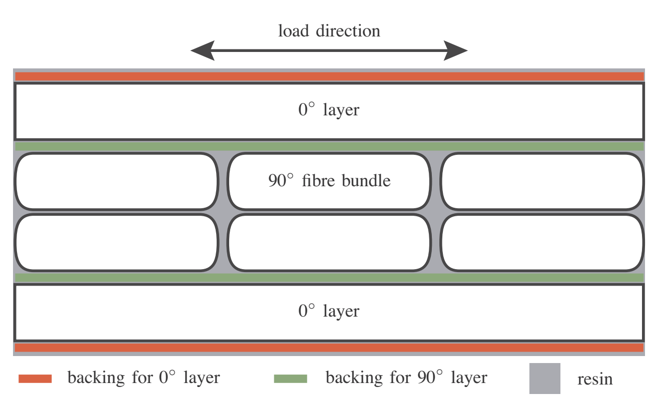

Fig. 2. Illustration of the tested lay-up. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)